Thickness dependence of critical Currents in CC: microstructure or pinning size effects?

Alex Gurevich

University of Wisconsin

Applied Superconductivity Center

Madison, WI

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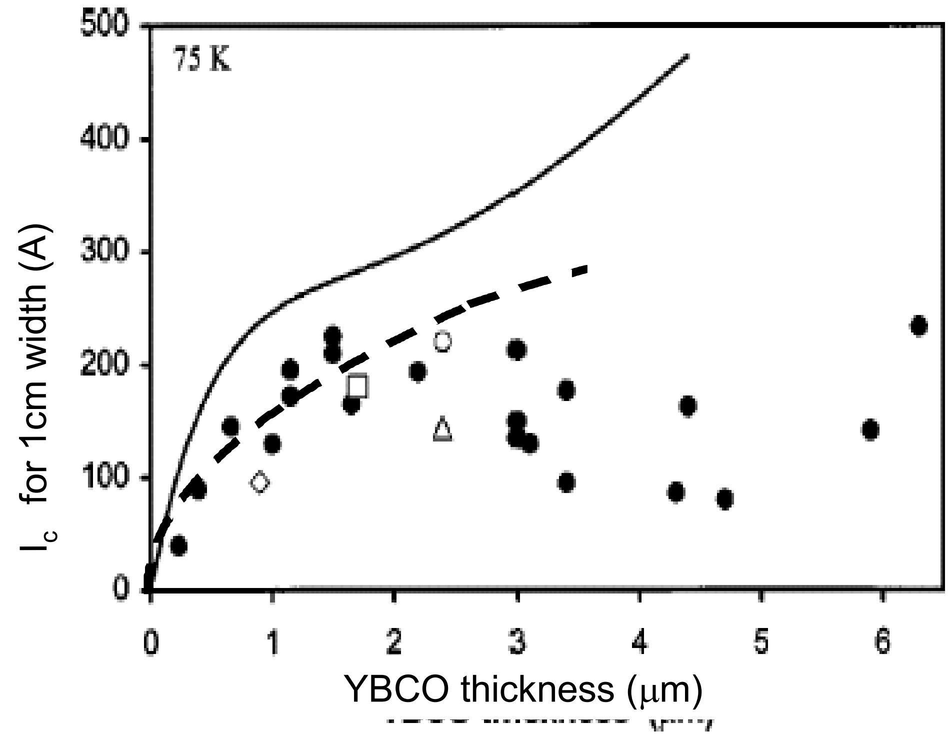
MOTIVATION

S. Foltyn et al.

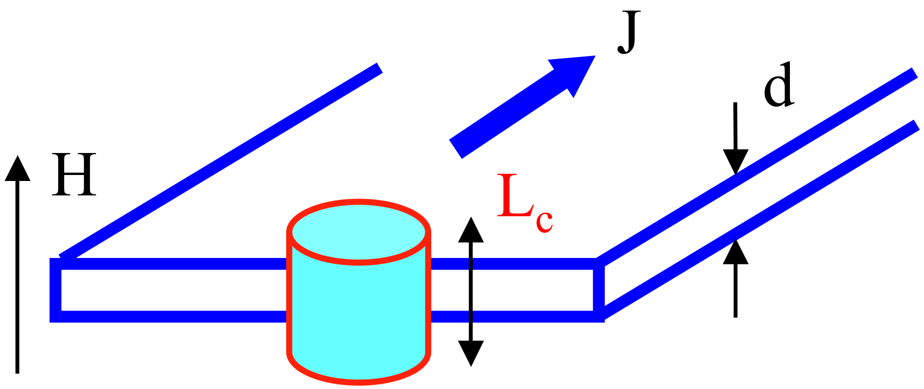
- Can pinning provide mechanisms resulting in the observed dependence $J_c(d)$
- Additional pinning centers, dead layers or size effects?
- Different mechanisms for zero-field and in-field J_c
- Self-field limitations
- 2D-3D dimensional crossover in single-vortex and collective pinning

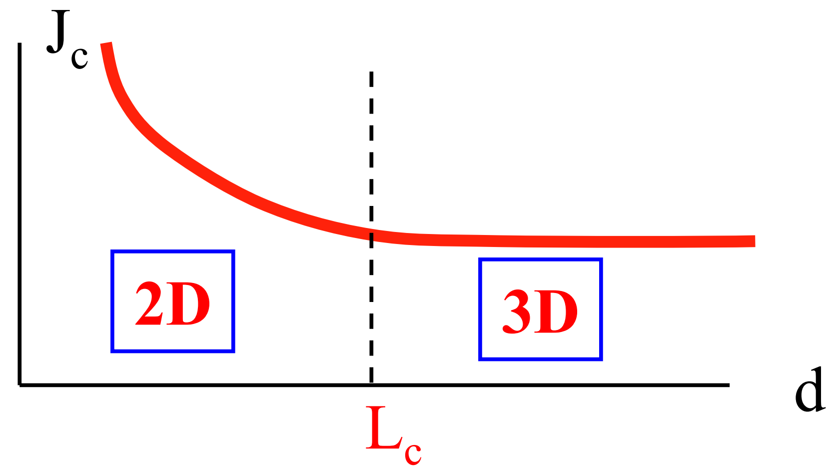


Add more YBCO, but I_c does not increases.

$I_c \propto \sqrt{d}$ (low fields)
$I_c \propto$ const (high fields)

SIZE EFFECT IN COLLECTIVE PINNING





- 3D-2D pinning transition if d < $2L_c$: $\mathbf{L_c} \Rightarrow \mathbf{d}$
- High-field thickness dependence (Kes and Tsuei, Brandt):

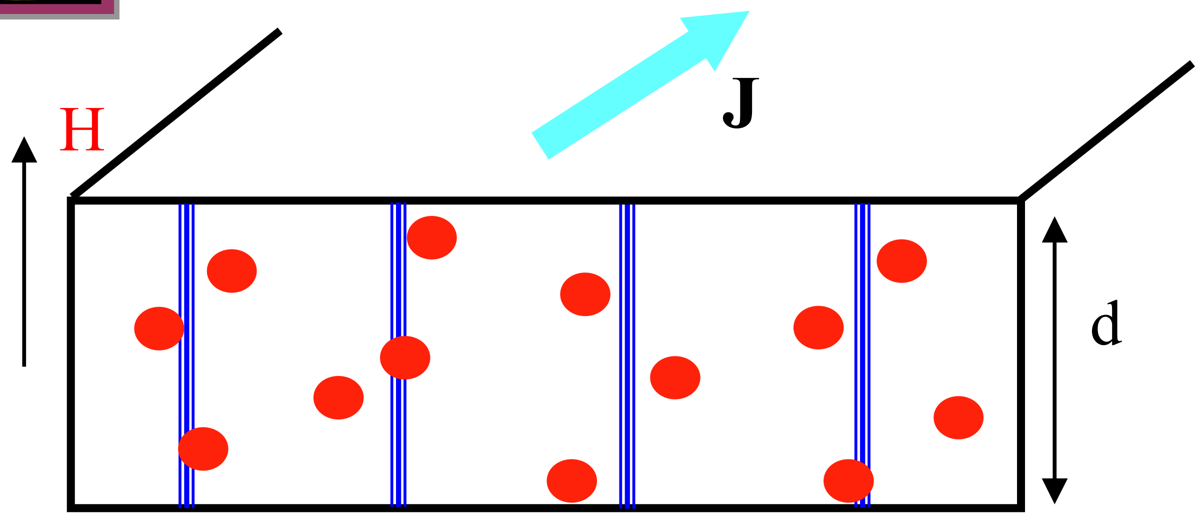
$$J_c \cong n_p U_p^2 / B r_p c_{66} d \quad \propto 1/d, \qquad I_c(d) = const$$

- Dimensional crossover in collective pinning (Wordenweber & Kes, 1986)

$$d[\mu m] < d_c \approx 2B^{1/4}[Tesla]/\sqrt{J_c}[MA/cm^2]$$

For B = 1T, and J_c = 1MA/cm^2, this yields $d_c \approx 2\mu m$

SINGLE-VORTEX PINING IN A FILM



- Rigid <u>infinite</u> vortex in a random potential: PINNING FORCE = 0
- Rigid <u>finite</u> vortex in a film: pinning force is FINITE.

$$\phi_0 J_c d \cong \frac{f_p}{\sqrt{N}} \times \frac{r_0}{l_i} \times N$$

$$J_c \cong \frac{U_p}{\phi_0}\sqrt{\frac{n_p}{d}}$$

$N = d/l_i$ is the number of pins per vortex, l_i is the pin spacing, $n_p = l_i^{-3}$, $U_p = f_p r_0$ is the pinning energy

Effect of thermal fluctuations

Fluctuating vortex in a pinning potential

$$\eta\dot{x} = \phi_0 J - \phi_0 J_c(d)\sin kx + \zeta(t)/d$$

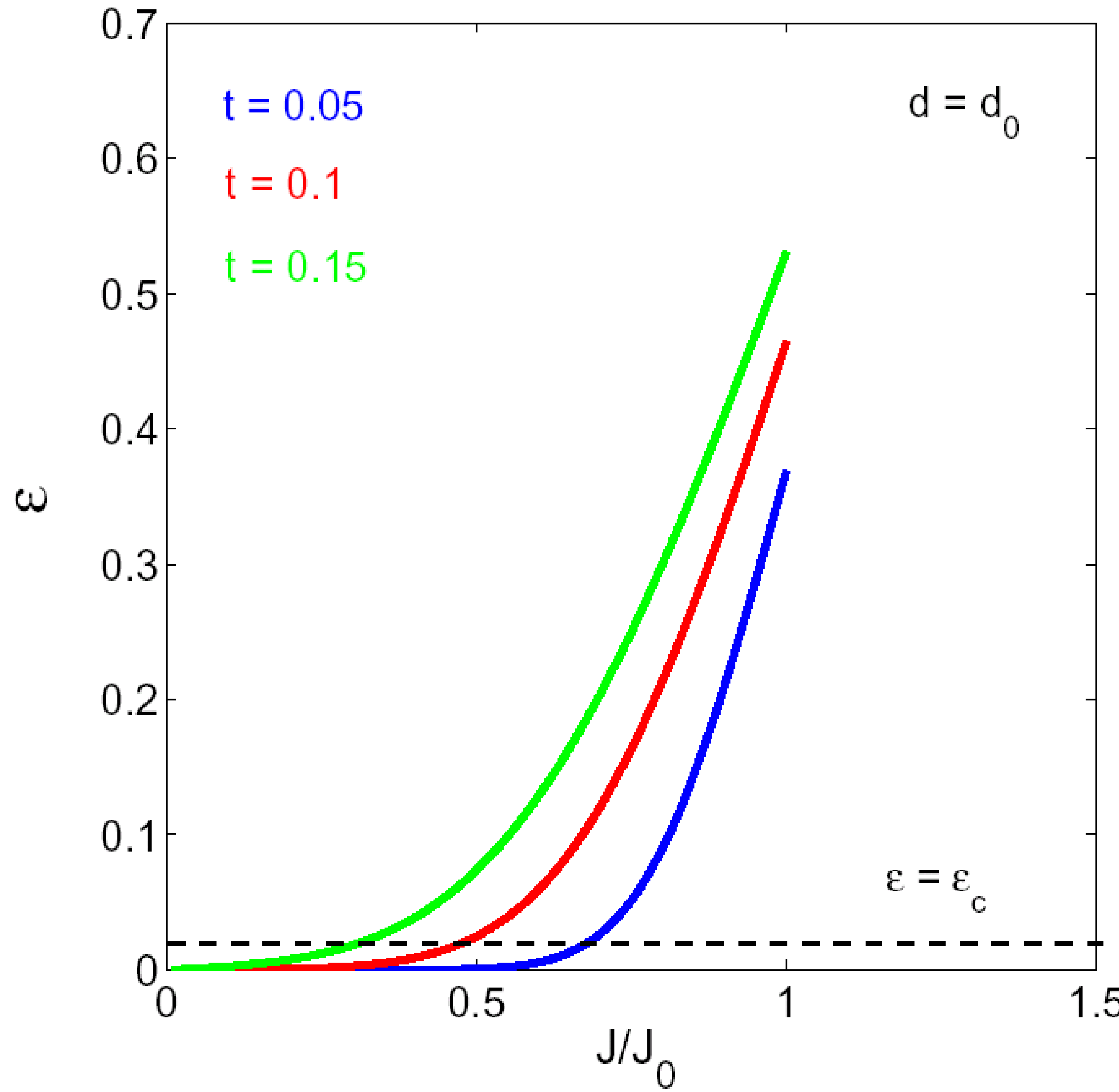
Same Eq. as for a Josephson Junction gives the exact E-J characteristics (Ambegaokar & Halperin, 1968)

$$\varepsilon = t(1-e^{-\pi\beta\alpha/t})/\alpha D, \qquad D = \int_0^{\pi} e^{-\pi\beta\alpha\theta/t} I_0\left(\frac{\sqrt{\alpha}}{t}\sin\theta\right) d\theta$$

Dimensionless parameters

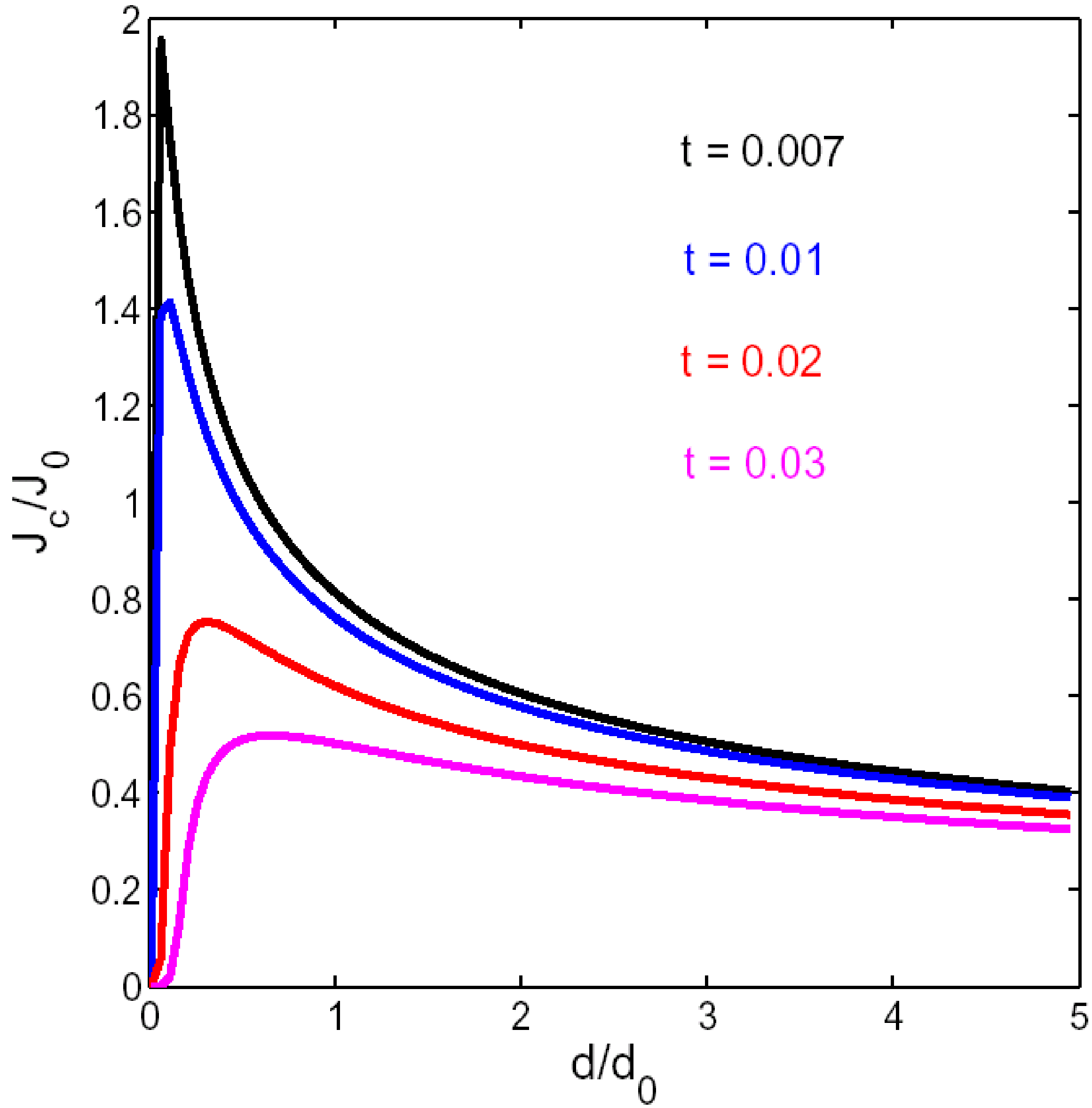
$$\varepsilon = \frac{E}{\rho_F J_0}, \qquad \alpha = \frac{d}{d_0}, \qquad \beta = \frac{J}{J_0}, \qquad J_c = J_0\sqrt{\frac{d_0}{d}}, \qquad t = \frac{\pi k_B T}{J_0\phi_0 d_0 r_p}$$

Current-voltage characteristics



- Exact E(J) as a function of T,H and d
- Thermal fluctuations broaden E(J) and reduce J_c
- Define $J_c(d)$ at a given electric field criterion
- $\varepsilon_c = E_c/\rho_F J_0 = 10^{-5}$ for $J_0 = 1$ MA/cm^2, $E_c = 1$ μV/cm, and $\rho_F = 10$ μΩcm

Thickness dependence of J_c



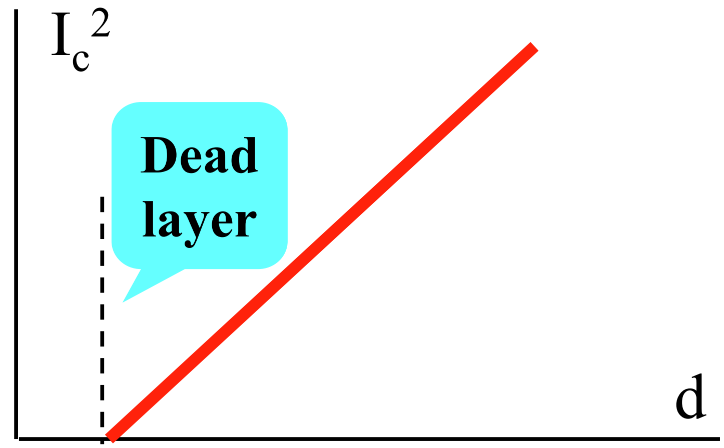
- Effective temperature:

$$t = \frac{\pi k_B T}{\phi_0 J_0(T,H) d_0 r_p(T)}$$

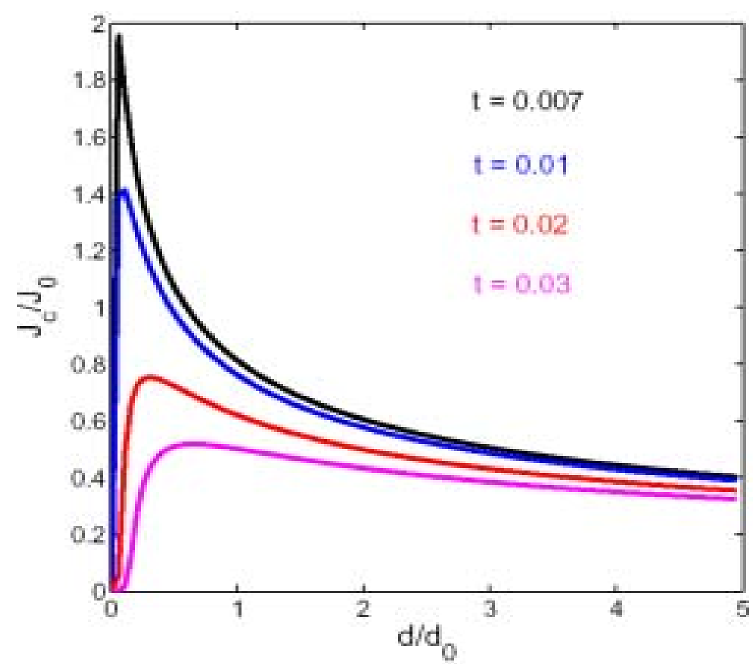
- Maximum at $d = d_m$ due to competition between pinning and thermal fluctuations
- As T and H increase, d_m increases
- Reveal the peak in $J_c(d)$ at higher H and T

Conclusions

Low T and H



High T and H



Distinctive features of the 2D pinning:

1. Square-root dependence of $I_c(d)$ at low H
2. Maximum in $J_c(d)$ at higher T and H
3. The maximum in $J_c(d)$ at higher T and H distinguishes the pinning size effects from microstructural factors (dead layers, etc).